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Ocean Bottom Seismometers for Research: A Reassessment

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FOR THE COMMANDER

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OCEAN BOTTOM SEISMOMETERS FOR RESEARCH: A REASSESSMENT

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ABSTRACT

An analysis of current ocean bottom seismometer technology has revealed that conventional, free-fall devices which simply rest on the surficial seafloor sediments could provide portable stations with short period performance only equivalent to the higher noise land stations located on islands. However, by emplacing borehole-type seismometers beneath the surficial seafloor sediments, the broadband performance of ocean bottom stations could prove superior to the best land stations. In fact, by combining "state of the art" broadband digital seismometers with modern deep sea drilling and ocean acoustic or satellite telemetry methods, permanent subseafloor stations with essentially real-time communication are entirely feasible. A plan for preliminary seismic research is suggested.

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I. INTRODUCTION

Significantly, the world's most tectonically active areas are near the deep ocean[1]. These areas include the entire Pacific margin (i.e., "the Ring of Fire"), the Alpine-Himalayan tectonic belt extending from the Mediterranean through the Middle East to Indonesia and, of course, the oceanic ridges (see Fig. I-1). In fact nearly all of this entire area is within 5° of international waters. Even the central Asian tectonic belt is only 20° from the ocean. Clearly land stations are not necessary to record data from seismic events in these high seismicity areas.

The use of ocean bottom stations for regional surveillance is predicated, of course, on the ability of such stations to detect and identify small events as effectively as alternative land stations. Unfortunately, adequate information is not available to assess the relative performance of ocean bottom stations in a near-in, or regional context. Previous experiments in the early 1960's indicated that ocean bottom stations would not be as effective as land stations for global teleseismic surveillance. This judgement was based on the observation that the background noise level, measured at several sites by short period seismometers, was much higher than land stations. The instruments were deployed by simply dropping them onto the seafloor mud and ooze. Although these instruments were not able to examine the long period noise which earlier workers suggested was comparable to land observations, extrapolation of the short period results suggested that long period noise levels would also be higher than land station levels. Accordingly, the concept of using ocean bottom stations for teleseismic research was abandoned in the late 1960's.

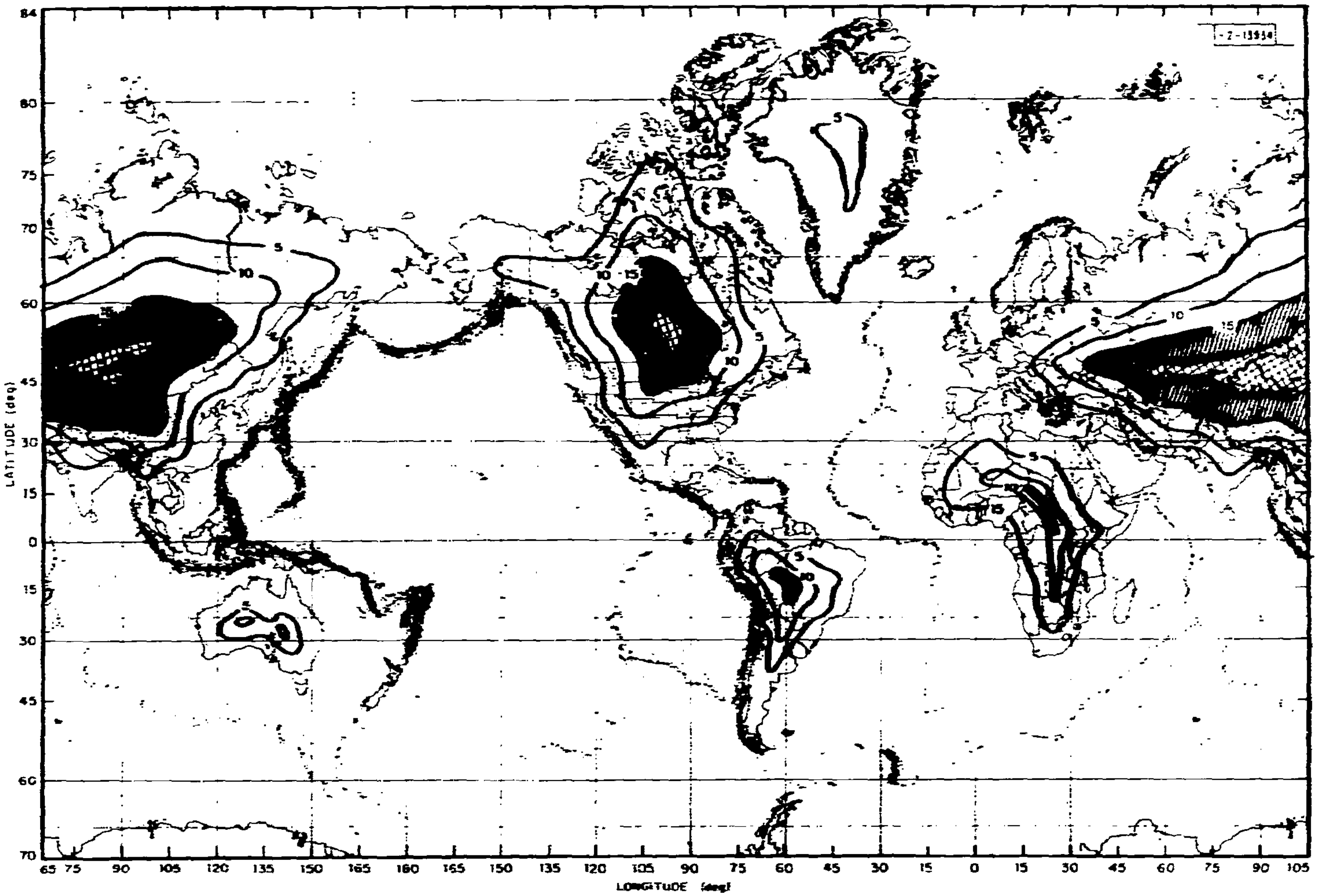

Fig. I-1. Chart showing world seismicity 1963-1972 and distance of all land areas, except Antarctica, from deep-ocean international waters. Contours are sketched in 5° intervals; hatched and crosshatched areas show regions greater than 15° (1665 km) and 20° (2220 km), respectively, from deep-ocean areas. Note that nearly entire earth's surface is less than 20° from deep ocean and that virtually all major seismicity zones are less than 5° from deep ocean.

Today such a judgement may no longer be valid in view of the substantial advances in oceanographic instrumentation and techniques for deploying and recovering seafloor devices. It appears that modern digital seismographs rigidly emplaced beneath the seafloor by deep sea drilling ships, manned submersibles or remote controlled manipulator ships can provide inexpensive ocean bottom stations useful for both long period teleseismic and short period regional monitoring. In fact, by incorporating modern acoustic data telemetering techniques, it should be possible to have essentially real-time monitoring comparable to land stations.

This report summarizes the role that OBS's might play in seismic research. Our approach is twofold, first, we discuss the advantages to using OBS stations that have come about from recent advances in ocean technology and second, we delineate the research tasks which should be addressed in the immediate future in order to accurately estimate the usefulness of such stations. We also present background material and a bibliography of pertinent references.

II. ADVANTAGES OF OCEAN BOTTOM STATIONS (OBS's)

A. Seafloor OBS's vs Land Stations

Aside from their obvious geographic desirability, OBS's may have important scientific and technical advantages over land stations for seismic research. Some of these are:

1. Increased Signal Amplitude

Although most previous experiments have probably not provided a faithful portrayal of true ground motion on the seafloor because of poor coupling and high noise, it is clear that signal amplitudes from earthquakes observed on the ocean floor are generally higher than those seen by a land station. For example, the ARPA-sponsored field tests off the Aleutian Islands in 1968 showed that OBS-calculated m_b values averaged 0.2 unit greater than land station calculated values. This was thought to result from the fact that the rays travelled a slightly shorter path to the ocean bottom stations and, more important, they did not have to propagate through a low Q continental crust. Also, more recent work has shown attenuation along oceanic lithosphere paths to be extremely small. Q values are estimated to exceed 6000. For the higher frequency band which will be particularly useful in regional monitoring, this signal enhancement could be significant.

2. Lower Noise

Deep ocean sites far from land would be relatively isolated from the sources of background noise likely to affect seismic stations. These are: cultural noise, breaking surf on coastlines, storm microseisms and local sea surface waves or tidal current effects. In practice this appears to be the case. Both the early work of Lamont and the later ARPA-sponsored Texas Instruments field tests showed decreased noise with increasing water depth and increasing distance from land. The dominant noise source is believed to be surf microseisms propagating out from the coastline as Rayleigh waves in the water mass and along the water-seafloor interface (Fig. II-1). The latter path is particularly energetic.

Table I lists representative noise levels observed on land and on the seafloor. Note that only the early Lamont workers reported short period noise amplitude levels comparable to those observed on land (i.e., 1 mμ p-p in the 2-10 Hz band). Indeed, these low noise observations prompted the first serious ARPA-sponsored inquiries into the utility of OBS's for seismic research. Unfortunately, the early low noise observations could not be substantiated in more extensive field tests carried out by T. I. in the mid-1960's. Noise amplitudes were typically 2 orders of magnitude greater than those reported earlier (i.e., 100-300 mμ @ 1 Hz).

It must be emphasized at this point that, after considering the field method used to make background noise observations, the above apparent high noise levels may not have been a true measure of solid-earth motions. In the T. I. system and for that matter with most systems: (i) the seismometers simply rested on surficial, unconsolidated seafloor sediments

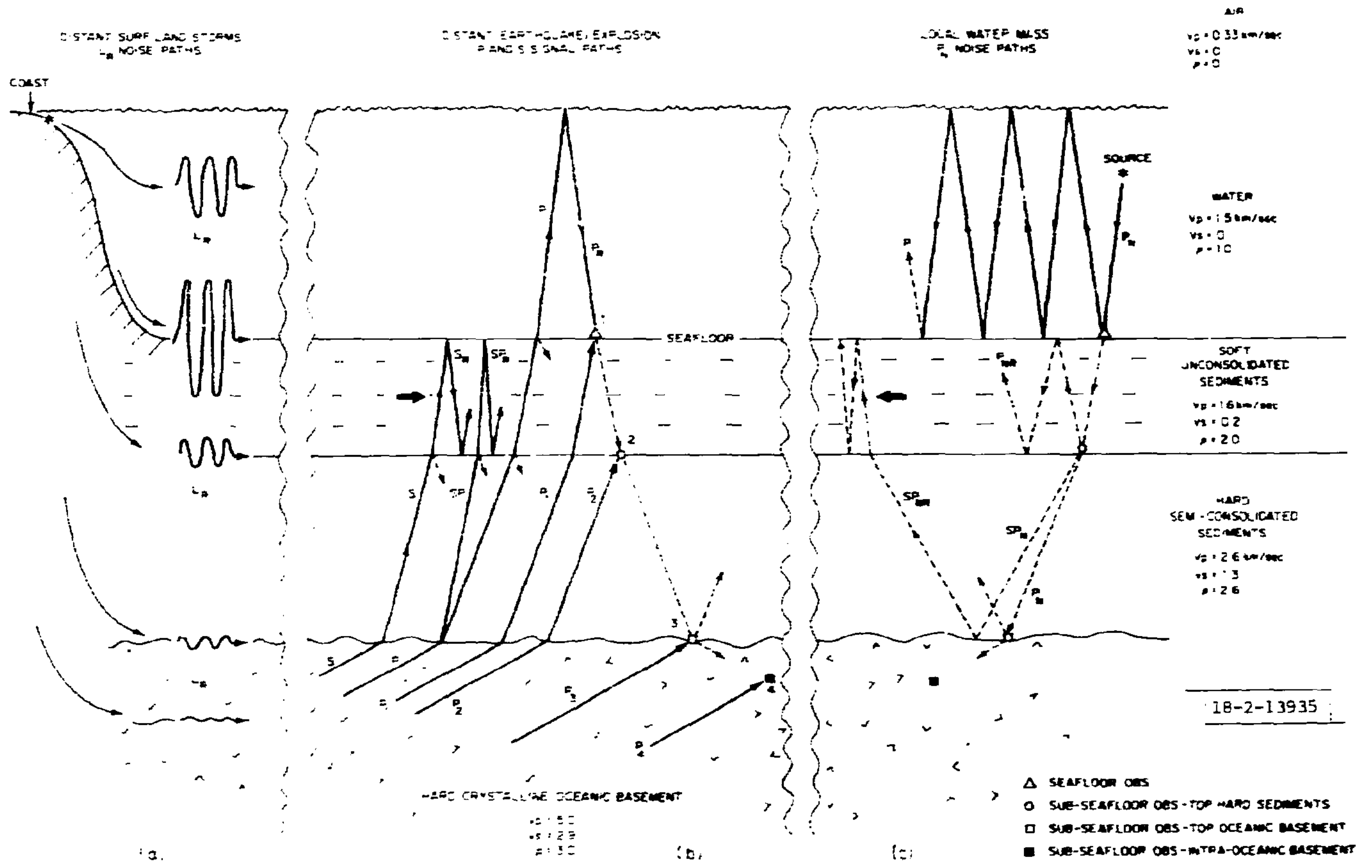

Fig. II-1. Schematic representation of seismic ray paths for ocean bottom environment. Strong signal ray paths are shown by solid lines in center portion of figure. Weaker paths are dashed and dotted. P and S arrivals from distant sources are shown at bottom. Relative magnitude of microseismic noise, which propagates as Rayleigh waves from coastline along various interfaces, is shown by amplitude of waveform symbols at left. Paths for local noise generated in water mass (currents, swells, ships, storms, internal waves) are shown to right. The propagation of trapped shear waves in soft surficial seafloor sediment layer is shown by heavy arrows.

and ooze whose seismo-acoustic properties were not much different than the overlying water mass (Fig. II-1; OBS position 1), and (ii) most systems used tall vertical frames which protruded into water mass to house their seismometers. These facts suggest that such devices probably recorded ocean water as well as solid-earth ground motion. Significantly, those seafloor instruments with seismometers well coupled to the solid earth and isolated from the "wind-like" motions induced on the housing frame by ocean currents and turbulence have shown short period noise levels approaching the 1-10 mμ levels observed at the better land SRO stations (Table I). These include the early Lamont devices of the 1950's (≈1 mμ) and the more recent Japanese and British OBS's (≈25-50 mμ). Notably, the ARPA-sponsored Texas Instruments devices of the 1960's and most U.S. devices developed subsequently have been plagued by much higher noise levels. Some show strong frame-sediment resonance.

No recent studies of long period seafloor noise have been made. In fact only the two long period OBS's developed at Lamont in the early 1960's have had significant recording durations. One of these, a shore cable connected system off California, was operated from the mid-1960's until the mid-1970's. Unfortunately no definitive analysis of noise observations from this device has been reported. However, information from a short duration recording (8.5 days) off Bermuda show noise amplitudes about 2 orders of magnitude greater than today's typical land SRO stations (i.e., 5 μ vs 50 mμ). Again these measurements are subject to the same doubts expressed about the short period observations in that these

TABLE I

COMPARISON OF SELECTED SRO STATIONS' NOISE BACKGROUND WITH OBS OBSERVATIONS

(Mean RMS Noise Amplitude-mμ)

Station/Investigators	Vertical Component Short Period (f_o)	Vertical Component Long Period (f_o)	Operational Dates
SRO's*			
Albuquerque, USA	0.38 (2.86 Hz)	9.56 (25 sec)	1977-
Mashad, Iran	0.57 "	8.20 "	1977-
Guam Island	40.25 "	11.25 "	1977-
New Zealand	28.92 "	45.92 "	1977-
OBS's			
Asada and Shimamura[3]	≈50 (2.7 Hz)	-	1972-
Francis et al.[4,5]	≈25-50 (8.0 Hz)	-	1972-
Texas Instruments Corp.[6]	≈100-300 (1 Hz)	-	1965-1968
Bradner[7] and Bradner et al.[8,9]	≈800 (1 Hz)	≈10000 (5-10 sec)	1964
Lamont			
Sutton et al.[10]	-	5000 (15 sec)	1965-1972?
Latham and Sutton[11]	≈5000 (1 Hz)	7000 (3.7 sec)	1965-1972?
Ewing and Ewing[12]	≈1 (2 Hz)	-	1959-1961

*Source: Texas Instruments Quarterly Report[2].

devices were essentially free-fall instruments resting on the sediment surface of the seafloor.

In summary it appears that the better free-fall OBS's existing today have short period noise levels approaching land stations. In any case, they are more than an order of magnitude quieter than the Texas Instruments devices of the 1960's. These low noise levels combined with the expected higher signal amplitude on the ocean floor suggests that even these simple seafloor-type OBS instruments would have a S/N ratio useful for regional monitoring. With improved coupling of the seismometers to the solid earth and their isolation from water motions and resonance effects, it is probable that subseafloor OBS's having long and short period S/N ratios higher than land stations could be developed for both teleseismic and regional research.

3. More Uniform Crust and Mantle Structure

The crust and mantle structure beneath the ocean basins is now known to be much simpler than that beneath the continents. The seafloor spreading hypothesis, generally accepted by ocean scientists to account for the formation of the seafloor, predicts that nearly horizontal sub-planar rock layers underlie most of the deep ocean. Only at mid-ocean ridges, deep trenches, and oceanic islands will there be significant lateral inhomogeneity of earth structure. Deep sea drilling, seismic refraction, and gravity and magnetic measurements support this hypothesis.

Such simple layering implies that large aperture arrays could be deployed to further improve the S/N ratio by beamforming or velocity filtering. In fact many of the signal processing problems caused by the near-field complexity of earth structure at land large aperture arrays (e.g., LASA, NORSAR) should not be encountered. By sharply reducing signal-generated coherent noise, a closer approach to the ideal $\sqrt{N}$ signal to noise ratio improvement might be realized. The widespread uniformity of earth structure beneath the ocean also implies that much larger arrays than those practical for land installation could be built.

4. Simplified Installation and Operation

The actual on-site deployment effort and costs, exclusive of ship transiting time, for dropping a free-fall OBS or even for drilling a borehole in the relatively soft seafloor materials will probably be comparable to the hard rock drilling necessary for installing SRO seismometers in remote areas of host nations. In any case, a borehole OBS station should only require a few days to install. Also, no borehole maintenance at a seafloor installation should be required because of ground water convection problems since the high conductivity, sub-seabed materials show small geothermal gradients and the ambient temperature is low.

The operational advantage of remote OBS stations may be significant since no on-site personnel are involved. Also, by employing acoustic data telemetering techniques, ship costs for data retrieval or costs for interconnecting cables or satellite telemetry necessary for real-time data links are eliminated. Furthermore, since acoustic telemetering is generally not limited to line of sight, data transmission would be difficult to interrupt at the site. In fact, deep sound channel (SOFAR)

hydrophones like the Air Force's Missile Impact Locating System (MILS) or naval systems could provide a reliable quasi-real time telemetry capability on a global scale. Of course, moored satellite telemetering buoys with only local short range acoustic links to the OBS's or a completely hard-wired cable system could be used. These approaches would probably make OBS costs more comparable to land stations.
However, by merging the seismic data telemetry with data from a hydroacoustic T-phase surveillance hydrophone moored above in the SOFAR channel, the OBS system becomes more attractive.

5. Greater Geographic Coverage

Since oceans occupy 70% of the earth's surface, it is difficult to infer the seismic structure beneath the ocean basins using only land stations. Observations made from island stations are likely to be unrepresentative of the broad ocean crust and mantle structure[13,14]. A well distributed network of ocean bottom seismographs and/or large aperture arrays would fill this gap in our knowledge. Also, the low level seismicity of such important features as trenchs and mid-oceanic ridges which are only accessible with OBS's can be examined. These observations could have important ramifications for general earthquake research.

B. Subseafloor vs Seafloor OBS's

The most effective method to improve both the signal coupling of OBS's to the solid earth and to isolate them from noise propagating in the ocean water and along soft sediment layer/water interface is to rigidly mount the seismometer beneath the soft sediment layer (Fig. II-1: OBS position 2).

1. Better Coupling to the Solid Earth

Competent semi-consolidated sedimentary materials are generally found a few tens of meters beneath the unconsolidated surficial seafloor sediments. These deeper, lithified layers show sharp increases in both compressional and shear wave velocities and bulk density. In fact the hard, crystalline igneous rocks of the high Q oceanic crust are usually covered by less than a few hundred meters of sedimentary materials in most areas. Accordingly, a borehole-type OBS installation, much like the present SRO stations, which is employed in the hard sediment or on/within the oceanic basement rocks (Position 3 or 4) should provide signal coupling vastly superior to free-fall devices resting on the soft sediment/water interface. Also, the signal amplitude can be maximized by simply adjusting the overall seismometer case density to match the acoustic impedence of the surrounding borehole rock materials.

2. Lower Noise

The depth of burial necessary for the seismometer to attain a significant noise reduction is probably only a few tens of meters due to the sharp gradient in the seismo-acoustic properties of the soft seafloor sediments. A buried seismometer is not only isolated from the wind-like noise induced by the ocean currents and turbulence on the housing frame but the soft overlying surficial material may act much like a soundproofing layer which will absorb ocean generated noise. In addition the air-water and seafloor-water interfaces will serve as efficient reflectors which effectively trap any propagating waves within the water volume (see right portion of Fig. II-1). Recent tests conducted at Woods Hole in shallow water showed more than a factor of ten reduction in local ocean-generated noise on a vertical component seismometer buried only 2 meters beneath the seafloor. Notably, some of the early Lamont OBS's which reported very low noise levels had their seismometers in probes which penetrated the seafloor a few meters.

The coherent microseism noise propagating as Rayleigh waves in the ocean water and along the seafloor sediment/water interface is also markedly attenuated with increasing depth since the shear wave velocity of the surficial sediments is only about 0.2 km/sec (see left portion of Fig. II-1). Thus, the microseism noise which is generated beneath breaking surf on distant beach surfaces does not penetrate very deeply into the soft sediment layer. Seismometers buried 300-600 meters beneath the seafloor would be virtually shielded from this dominant source of seafloor noise.

3. Reduced Signal Contamination

Seismic signals received at a seafloor OBS travel through the ocean water as well as through the solid earth beneath the station

(Position 1 in Fig. II-1). Those rays arriving at the OBS which are reflected from the local air-sea surface interface, particularly contaminate the direct seismic arrival phases. This signal-generated noise not only introduces apparent complexity and reverberation in the wave train coda but they also tend to generally reduce signal amplitude because of interference. Accordingly, by locating the seismometer in a borehole beneath the seafloor surface, seismic signal entering the overlying water mass and soft sediments will be effectively trapped much like noise initially generated in the ocean. In fact, seismometers near the oceanic basement-hard sediment interface (Positions 3 and 4) should be virtually free of reflected arrivals returning from overlying interfaces.

III. SUGGESTED INITIAL STUDIES

In order to accurately assess the utility of OBS's for seismic research the following investigations should be undertaken.

A. Determination of the True Solid Earth Noise Background on and beneath the Seafloor

1. Subseafloor Noise Measurements in Boreholes

An ocean field program using the current borehole-type SRO seismometers should be initiated to obtain seafloor and subseafloor noise observations. This program could be started immediately using the Geotech model 44000. This unit is specifically designed to fit in standard 4" exploration pipe used by ocean drilling ships. These seismometers, after appropriate field testing and modification for marine use (see study D below), could first be lowered into the many existing oil exploration wells for long and short-term, shallow water measurements at various locations. Next, deep water measurements could be made using holes drilled by the Deep Sea Drilling Program (DSDP) ship GLOMAR CHALLENGER.

For the deep water studies there are three possibilities: a. The work might be done as an integral part of the GLOMAR's normal cruise operations. b. It is also possible to use a separate remote manipulator-type ship such as the ALCOA SEAPROBE or GLOMAR EXPLORER to re-occupy previously drilled holes and implant the seismometers. This latter approach is likely to be more suitable for longer term observations which otherwise would interrupt the CHALLENGER's schedule. However, arrangements would have to be made with DSDP to leave hole re-entry cones and acoustic transponders necessary for relocating the site. c. For shallow penetration deployments in soft sedimentary materials, a manipulator ship alone could independently implant seismometers using conventional "wash down" techniques. This approach might be the most economical and convenient if it is found unnecessary to drill into the hard ocean basement to achieve optimum S/N ratios.

2. Noise Analysis of Previous and Current Seafloor-type OBS Data

Along with making new borehole observations, existing long and short period seismograms from the better-designed seafloor OBS's should be examined for noise levels. Observations made on hard igneous rocks should be particularly valuable. The British and Japanese instruments are most likely to be most useful for short period observations. For longer period studies, the shore-cabled instrument operated off California (Pt. Arena) during the mid 1960's-mid 1970's interval is probably the only useful data available.

B. Signal Level Comparison between Land and OBS Stations

A comparative study of the magnitude and spectral content of events recorded at both OBS and land stations should be made using both long and short period data. The seafloor OBS device which operated off California during the period of extensive U.S. and Soviet underground testing in the late 1960's will provide the most useful long period data. Unfortunately, for short period comparisons, few of the current seafloor OBS's have recorded teleseismic events. Exceptions are the

Japanese devices deployed near the Japan and Kuril-Aleutian Trenches. Also, further analysis of records from the quieter Texas Instruments devices could prove suitable. None of the current OBS's are believed to have recorded nuclear explosions. For the subseafloor OBS signal amplitude comparisons, future earthquakes and explosions recorded during the routine borehole noise monitoring program outlined above will provide the first useful data.

C. Waveform Discrimination Studies

While it is likely that the well-known waveform discriminants (e.g., M_s vs m_b, depth) developed for land station research will be applicable to ocean bottom stations, some differences in seismic arrival signatures of both explosions and earthquakes are probable, particularly for those stations with seismometers buried deep beneath the seafloor. Clearly these stations will not be on the free-surface approximated by land stations. With 5 km of water and up to 1 km of seafloor sediment above them, these seismometers are essentially enclosed in the vibrating medium. Accordingly, a research program to study the response characteristics of seafloor seismograms and their comparison with waveform discriminant interpretations from land stations should be initiated. This work might involve field experiment as well as laboratory analyses and should begin as soon as it appears that OBS's may be useful for seismic research.

D. Marine Adaptation of SRO Land Seismometers

Although it appears that the borehole SRO seismometers (i.e., Geotech models 36000 and 44000) will be ideally suited to marine deployments, these units have not yet been tested or adapted for use on the ocean floor. Thus, it is essential that field testing to determine if equipment or design concept modifications are required begin as soon as possible. Initial studies should be done in shallow water where the instruments can be deployed in boreholes without need of large, expensive drilling ships. Also direct data recording can be done by using a short cable link to a nearby ship, platform or shore base.

In addition to the basic evaluation of equipment design, signal amplitude and background noise level measurements at various depths beneath the seafloor should be an essential part of these studies. Also, a comparison with conventional seafloor-type OBS's which simply rest on the soft sediments would be useful. The execution of such borehole seismometer tests would probably require a controlled environment much like that utilized recently by the Office of Naval Research (ONR) to evaluate current free-fall seafloor-type OBS designs. These evaluations were done in cooperation with the U.S. Navy Torpedo Test Facility on Puget Sound during June 1978. Navy divers and ships were used for instrument deployment and recovery. Real-time on-shore data recordings were made by linking the OBS's to an underwater cable network. ARPA participation in these types of experiments in the future might be advantageous.

For deep water feasibility testing of the borehole SRO seismometers, off-shore oil drilling platforms can be used. The seismometers could be deployed in previously drilled holes, at relatively low cost, to gain important information.

IV. ADVANCED RESEARCH

A. Systematic Global Deployment

If the signal and noise analyses outlined above show encouraging results, a more systematic field program would be appropriate. Both borehole and free-fall units might be deployed for longer periods of time in regions of specific interest (e.g., Kuriles, Kamchatka, Aleutians) as well as on a global scale. For this work a ship dedicated to OBS deployments might be advantageous. Internal recording devices whose data could be physically recovered or acoustically telemetered periodically to surface ships or submarines would probably be the most effective data retrieval method.

B. Remote Station Installations

Assuming that the global deployments indicate a significant advantage to using borehole OBS's for seismic research, semi-permanent stations with data transmission links to shore bases could then be installed in specific regions of interest. These links could use acoustic telemetry, satellite telemetry, or cables to transmit the data. Nuclear power units would be required for long term operations. Geophysical studies of the seafloor structure between the station and the region of interest should be made to insure that maximum S/N ratio is attained. Intervening low Q zones should be particularly avoided for regional monitoring.

C. Remote Arrays

After the completion of a remote network of subseafloor OBS's, it may be appropriate to install large aperture arrays to further improve signal detection thresholds and discrimination capability for a specific region. Again, geophysical studies of the seafloor structure should be made before installing such arrays to insure a maximum S/N ratio.

APPENDIX I - BACKGROUND MATERIAL

A. Evolution of Ocean Bottom Seismographs

1. Early Studies

Ocean bottom seismographs have been in use since the late 1930s. The first instruments were either tethered or free-fall short period devices with internal recording. They were basically designed for conducting seismic refraction studies of crustal structure[15,16]. The work was supported by the U. S. Navy. After World War II, interest in microseism phenomena[17] brought development of lower frequency (2 Hz) devices which could acoustically telemeter data to a nearby ship[12]. The instruments were also used for seismic refraction and earthquake recording. These instruments showed good signal to noise ratios. Background noise amplitudes at deep stations (>4800 meters) far from land (>500 km) were reported to be less than 1 mμ in the 2-10 Hz frequency band (Table I). These measurements were comparable to the existing land station observations of about 1 mμ @ 1 Hz[18].

These early low noise measurements spurred further development of even lower frequency (f_o = 1 Hz) short period ocean bottom devices and a true long period (15 sec) instrument. The devices described by Sutton et al.[10] had marked negative buoyancy (500-750 kg) and were deployed using tethered anchors. They telemetered their data either electrically via a cable to shore or acoustically to a nearby ship. The devices of Arnett and Newhouse[19] and Bradner et al.[8,9] were ballasted free-fall instruments with slight positive buoyancy. All of the above instruments, save the Bradner et al. device

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which inserted a short spike into the seafloor much like the early Ewing and Ewing[12] instruments, simply rested on the seafloor sediment-water interface.

Initial observations with these instruments suggested that ocean bottom signal amplitudes were higher than those at land stations, particularly at higher frequencies. However, the lower frequency background noise level also appeared to be higher[7,9-11,20-24]. Sharp noise peaks in the 3-6 Hz band were also noted. The dominant low frequency noise (7-8 sec period) was generally attributed to breaking surf-induced microseisms propagating from coastlines as Rayleigh waves as well as from local pressure-induced disturbances due to ocean swells passing over the instrument site. The higher frequency noise peaks were thought to be related to current disturbances transmitted through the instrument frame. The increased signal amplitudes were believed to result from reduced attenuation due to the absence of a thick low Q continental crust beneath an ocean bottom site and possible focussing effects of air-sea surface reflected rays returning to the seafloor. In general, these first programs concluded that the ocean bottom could prove to be useful for seismic research purposes. However, the somewhat higher than expected noise levels suggested that more representative noise measurements in the world's oceans should be made, especially at sediment-free sites[11].

2. Texas Instruments Experiments

In order to assess the potential S/N ratio advantage of OBS's and to evaluate their operational feasibility for global scale nuclear monitoring, the Texas Instruments Corp. (T.I.) conducted extensive field tests during the 1966-68 period[6,25,26]. Instruments similar to those described by Arnett and Newhouse[17] were deployed near the Kuril (1966) and Aleutian (1967/68) Islands and in the Gulf of Mexico (1967). Nearly all sites were in regions of thick sediment cover. The tests generally confirmed the increased signal amplitudes found by the earlier workers. However, the enhancement was not as dramatic as expected. For example, the average m_b magnitudes of earthquakes with periods averaging 0.6 sec (1.67 Hz) were only 0.2 units higher than those calculated from land stations for the same events. Similarly, the low noise levels reported by earlier workers could not be duplicated. In fact, the lowest short period noise amplitudes were about 100-200 mμ, not the 1 mμ result of Ewing and Ewing[12]. However, the T.I. experiments were able to confirm the general decrease in noise with increasing water depth (>4000 m) and distance from land (>250 km). Unfortunately the character of the long period noise spectra below about 0.2 Hz could not be directly examined with the 1 Hz T.I. instrument.

These disappointing results proved crucial to further development of OBS's. First, they suggested that since virtually no signal improvement was gained in the short period band and that background noise amplitudes were about 2 orders of magnitude higher than those at land stations, poorer

S/N ratios were likely for OBS's, no matter where they were deployed, compared to land stations. Second, by extrapolating the short period noise spectra curve to lower frequencies (<1 hz), it appeared that OBS's would be even less useful than land stations for long period teleseismic research.

This assessment, combined with the anticipated greater expense of OBS stations due to high initial costs, time-consuming deployment and recovery methods, and high loss rate, as well as the rapid advances then being made in digital signal processing of land seismometer array data, terminated further work on OBS experiments. Emphasis turned toward the high gain large aperture arrays such as LASA, NORSAR, and ALPA for teleseismic nuclear monitoring and research.

3. Recent OBS Related Developments

Following the earlier experiments, marine seismologists shifted their interests toward simple short period ocean bottom seismometers and hydrophones useful for seismic refraction and local microearthquake studies. The Office of Naval Research (ONR) and the National Science Foundation (NSF) maintained modest efforts at Scripps Institution of Oceanography[17-32] and Lamont-Doherty Geological Observatory[24,33,34]. Also, the British (IOS)[35-43], Japanese (Univ. of Tokyo)[44-53], and the Soviets (Moscow)[54-57] continued to develop instruments. Free-floating hydrophone systems (SONOBUOYS) were also extensively employed for both seismic reflection/refraction and microearthquake studies[58-67].

In the mid-1970's renewed enthusiasm for short period OBS's was generated by various scientists working on earthquake tectonics at plate boundaries (i.e., ridges and trenches) and detailed oceanic crustal structure. Beginning in about 1973 naval interest in the acoustic-seismic layering of the seafloor and new thrusts in earthquake prediction have brought increased support from ONR and NSF, respectively. New additional marine seismology groups have sprung up in the U.S. at the Universities of California (Santa Barbara[63]/Scripps)[64-68], Texas (Galveston[69]/Austin), Washington[70,71], Hawaii[72-74], Oregon[75], Lamont Doherty[76,77], Massachusetts Institute of Technology[78,79] and Woods Hole[80]. In Europe marine seismology efforts have been recently initiated in France[81,82], Germany[83], and Britain[84]. Also the Canadians (Bedford Institute) and Australians (Australian National University) are beginning to develop instruments. Nearly all of the instruments currently operating are of the free-fall, internal recording type which simply rest on the seafloor. The Japanese, German, and the British shallow water system are tethered to an anchor and surface buoy. Some of the Hawaii OBS's telemeter their data via a cable to shore or are radio-linked via a surface buoy. Most are short duration analog recording devices with record intervals ranging from a few hours to about 30 days. The Scripps and MIT systems employ a digital recorder. Hawaii and Lamont also plan digital systems.

The general performance of these recently developed OBS's has been uneven to say the least. The most notable successes in attaining high S/N results have been made by the British[5,36] and Japanese[3,85] workers in their studies of microearthquakes near ridges and trenches, respectively. The British units have been able to record local ridge crest events (>10-20 km away) as small as M_L magnitude 0 in the presence of short period noise of about 25-50 mμ[5]. The Japanese instruments show similar high performance results. In fact, the Japanese OBS's have been able to demonstrate that the oceanic lithosphere in the western Pacific shows very low attenuation. Q-values often exceed 6000 along paths extending over 1000 km seaward from the Japan-Kuril trenches[3]. Walker et al.,[86] have confirmed these high Q-values using ocean bottom hydrophones. Clearly, the better OBS instruments of today have about an order of magnitude higher S/N ratio than the various devices built by Texas Instruments in the mid-1960's.

British and Japanese workers using essentially the same units discussed above have also carried out seismic refraction studies on the mid-Atlantic ridge and in the western Pacific[3,87]. In fact, the Japanese have been able to detect refraction arrivals from 2 kg charges detonated in water at distances of more than 100 km.

Relatively few results have been reported to date by the many other groups currently developing OBS's. Significantly no background noise measurements are available. Most of these devices have been plagued by two major geophysical problems; namely, poor solid-earth coupling which has resulted in low signal response, and failure to isolate the seismometers for ocean water-induced motions which has caused high background noise. Also, inadequate engineering efforts have resulted in a variety of equipment malfunctions.

The former geophysical problems are the most serious. They both probably result from the fact that most OBS's simply rest on low density, unconsolidated surficial sediment layers whose seismo-acoustic properties are not much different than the overlying seawater (Fig. II-1). That is, their compressional wave velocities V_p are nearly equal, (1.5 vs 1.6 km/sec) while the shear wave velocity V_s of the sediment is typically only 0.1-0.2 km/sec[70,88-90]. Consequently, most free-fall OBS's are in a mechanical environment more representative of the ocean water than the seafloor rocks. They are certainly not on the free surface of the solid earth crust as are land seismometers. Thus, the motion of the ocean is well-coupled to the instruments, particularly in those nearly buoyant OBS's with tall vertical-frames housing their seismometers, while seismic arrivals are damped considerably due to the poor acoustic impedence matching with the harder subseafloor layers.

The British and Japanese devices appear to have overcome the noise coupling problem by restricting their experiments to regions where bare rock outcrops on the mid-Atlantic ridge (i.e., the British) and by judicious design of the seismometer and its housing frame (i.e., Japanese instrument). The Japanese device is particularly well suited for sediment coupling in that the sensor recording system is housed in a long nonbuoyant cylinder which lies horizontally on the seafloor. It presents a very low profile to any ocean water disturbances much like the early devices described by Ewing and Ewing[12]. Nearly all other current devices incorporate a tall tower-like frame with buoyant pressure sphere near their tops to house instruments and expendable ballast anchors at their bases to provide only slight negative buoyancy. The latter arrangement not only couples poorly to the sediment but it may also respond much like an inverted pendulum. It is probably quite susceptible to resonance and ocean water perturbations.

Another factor which should be considered for an OBS resting on or in the soft surficial sediment layer is the likelihood that this layer will behave as a waveguide. The sharp shear wave velocity gradient below and above the layer means that shear waves (S) emergent near an OBS may be trapped between the water and the deeper hard sediments and rock (Fig. II-1). In fact, very strong prolonged signals, particularly on the horizontal component, are usually observed in marine refraction studies which tend to contaminate the direct arrivals[91,92]. These signals are not seen on nearby hydrophones. These effects have served to complicate interpretation of seafloor OBS data recorded in regions of thick sediment cover.

The major problems of OBS equipment design deficiencies and malfunctions have been: (i) complete failure to recover the free-fall instruments, (ii) failure of recording and control system to function properly in the deep ocean environment, and (iii) housing frame resonances. All of these problems seem to have a common origin: lack of a coordinated program to develop a comprehensive design among the many investigators.

This situation is understandable when one considers that OBS groups in the U.S. are independently directed by more than 10 marine scientists operating with small budgets from several agencies with diverse interests. These agencies have included ONR, NSF, USGS, and ERDA. Consequently, the emphasis of most programs has been to get a modicum of results as quickly and as cheaply as possible. Relatively little effort has gone into the design of more reliable and less noisy instruments. In fact, only those groups closely associated with large ocean-oriented engineering centers have been able to take advantage of the major advances made in ocean technology since 1968. For example, the acoustic release transponders, digital microprocessor recording and control techinques, and laboratory deep ocean simulation testing common at oceanographic centers today are not incorporated in most OBS designs.

4. Current OBS Research

The recent efforts of the U.S. Navy to determine the small scale seismo-acoustic structure of the oceanic crust and lithosphere has prompted the Ocean Acoustics Division of ONR to form a working group of U.S. scientists whose responsibility is to outline important objectives[93]. This group has produced a series of recommendations for future research. A major component of their proposed study includes the use of ocean bottom seismometers (OBS's) and hydrophones (OBH's) for refraction and reflection measurements[92]. These recommendations combined with the rather lackluster performance of current U.S. ocean bottom seismograph programs has spurred ONR to undertake a systematic evaluation of current OBS designs. The essential element of this evaluation was a shallow water field test of the various OBS systems in Puget Sound during June 1978. Ten university groups participated in the tests. Background noise, microearthquake response and explosion signal levels were compared. A report on these tests should be available in early 1979[92].

The Puget Sound test was designed as a forerunner to a major seismic refraction/microearthquake investigation of the East Pacific Rise structure off Mexico planned for 1979 (Riviera Oceanic Seismic Experiment = Project ROSE). This will be a U.S. multi-institutional study and will utilize primarily free-fall short period OBS devices with internal recording as well as conventional surface ship seismic studies. A large array of about 40 seismometers with dimensions on the order of 100 km will be deployed over the Riviera fracture zone (21°N). Hydroacoustic studies will also be done. Seismologists at Hawaii have further suggested deployment of a short period seismometer in a GLOMAR CHALLENGER hole which may be drilled in the ROSE area[94]. Also the Scripps and Lamont seismology groups hope to deploy some longer period (10 sec) seafloor-type OBS systems.

More recently, Woods Hole scientists[80] initiated an ocean bottom seismic study comparing free-fall instruments that rest on the bottom in a typical OBS tripod array with others that are driven into the sediments on a probe, much like the early devices of the 1950's described by Ewing and Ewing[12]. Significantly, shallow water tests showed that the probe noise level was more than an order of magnitude lower than the tripod and was independent of local ocean water motion (e.g., tides, surface currents, and surface waves). However, no difference in signal level was observed for explosive charges fired up to 4 km away.

In a most recent OBS experiment, D. A. Matthews and R. Stephens of the University of Cambridge (England) successfully deployed a commercial, 3-component short period seismometer down a borehole drilled by the GLOMAR CHALLENGER north of Puerto Rico (Site 417/418) in water over 5500 meters deep[95]. The purpose of the experiment was to conduct a fine scale oblique reflection and refraction study of oceanic layers 2 and 3 and the overlying sediments. Although electrical noise associated with the drill string prevented the use of maximum sensitivity of the instrument, background noise levels were much lower than expected. In fact, seismic noise amplitudes were estimated to be much less than 120 mμ at 10 Hz.

B. Modern Land Seismographs

The gradual evolution of ocean bottom seismographs (OBS's) over the last 40 years has been far outpaced by the major advances made in land seismology and marine technology during the last 10 years. Those advances in seismic techniques which have yet to be utilized in OBS applications include the following:

1. Seismic Research Observatories (SRO's)

A global network of ultra-sensitive seismological stations is currently being established under ARPA sponsorship[96]. These stations incorporate digital feedback 3-component seismometers (Geotech 36000) which have a dynamic range of about 120 db in the 1-100 sec band. In order to reduce background noise at these stations, a cylindrical shaped seismometer case (≈6" dia x 8' length) is deployed in a borehole about 100 meters deep. Noise levels for stations far from the ocean coastline (i.e., Albuquerque, Mashad) are typically 0.5 mμ (SP) and 10 mμ (LP). On islands (i.e., Guam, New Zealand), the levels are about an two orders of magnitude higher (see Table 1). Thus the best SRO land stations show short period noise levels about 2 magnitude units less than the best OBS operating today while island station performances are about equal to current OBS's. Note that SRO long period noise levels are more than 2 orders of magnitude lower than even the early Lamont OBS's[10,11].

2. Borehole-type Seismometers

The high performance aspects of the borehole SRO type seismometer make it likely that similar systems will be used for future seismological research. Accordingly, Teledyne-Geotech has recently developed a miniaturized prototype of an SRO-type seismometer (Model 44000) suitable for future deployments in conventional 4" ID oil exploration drill pipe[97]. This unit's performance is similar to the standard model 36000 but it is broader band, 0-50 Hz.

The Model 44000 can be oriented and will level itself in holes drilled as much as 15° off-vertical versus 5° for the Model 36000. Both instruments are also designed to withstand high pressure in order to facilitate their use as logging tools in commercial deep oil drilling applications. These characteristics all combine to make the borehole SRO-type instrument ideally suited for subseafloor OBS applications. In fact, the model 36000 can be deployed without major modification in the 11" diameter cased boreholes currently being drilled by the GLOMAR CHALLENGER.

3. Digital Signal Analysis

The widespread deployment of land seismic arrays (e.g., LASA, NORSAR, ALPA) and the global SRO network has spurred development of advanced digital processing to handle the large amount of data they generate. Today most modern automatic detection and discrimination techniques are largely based on the fact that the data is in digital form on a quasi-real time basis[98]. Significantly, few of the current OBS devices have digital recording. Most rely on internal analog magnetic tape which must be digitized after recovery of the device from the seafloor. Clearly the full power of digital processing would be difficult, if not impossible to apply to such OBS's in a research mode.

C. Modern Marine Technology

The dramatic progress made in verifying current models of ocean basin formation (plate tectonics) and the circulation of the oceans and atmospheres has been brought about by technological innovations introduced largely since 1965. Those innovations relevant to future OBS studies include: deep sea drilling, remote viewing and tool manipulating, manned submersible vehicles, long term moorings, acoustic telemetry and command-control systems, portable nuclear power units, and satellite telemetry. None of these techniques were operationally available to the ocean science community in 1968.

1. Deep Ocean Tools and Research Vessels

Perhaps the most important advance in ocean technology has been the development of sophisticated tools and research vessels. These advances have revolutionized the way ocean scientists now approach seafloor research problems. In the past many scientists considered the ocean floor to be about as remote as the surface of the moon. Today, due to the innovations mentioned above the sea floor is no more inaccessible than remote land areas.

a. Remote Controlled Manipulator Ships

Following the loss of the U.S. nuclear submarines Thresher (1963) and Scorpion (1968) in the Atlantic and a U.S. nuclear weapon and two foreign submarines in the Mediterrean Sea, the U.S. Navy undertook a program to develop a deep ocean search and salvage capability. There was also a requirement for installation and recovery of various equipments to support naval submarine surveillance operations.

To meet these needs, several ships and devices have been developed which allow operators on surface vessels to examine the seafloor and to manipulate tools at the end of long pipes, tethered cables, or on free-swimming vehicles. These systems include the civilian ships GLOMAR EXPLORER (Global Marine Corp.) and SEAPROBE (Woods Hole Oceanographic

Institution and Alcoa Corp.) which mount their manipulator tools at the end of a long pipe. These ships have very large lifting capacity (>150 tons). Naval systems include CURV, a tethered device, and a variety of free-swimming vehicles. There are also several naval submarine rescue ships with manipulator capability. Together, these systems can operate in nearly all ocean depths and can perform tasks ranging from the delicate insertion of a lift hook into a small ring attached on a sonar projector frame (SEAPROBE) to raising large portions of a Russian nuclear submarine (EXPLORER). Also, CURV was used to recover a nuclear weapon off Spain. Clearly, any reasonably large object can be remotely installed and recovered from the seafloor today by surface ships.

b. Manned Deep Submersible Vehicles

During the late 1960's the U.S. Navy also spurred development of small manned submarines to assist in search and salvage operations as well as in equipment installation and recovery tasks. They were also planned as oceanographic research tools. These vehicles include the DSRV ALVIN, operated by the Woods Hole Oceanographic Institution and sister-DSRVs SEACLIFF and TURTLE, which are operated by the U.S. Navy. A nuclear research submarine, NR-1, and the bathyscaph, TRIESTE, are also U.S. Navy vehicles. The French Navy operates the deep research submarine CYANA. The above vehicles, all developed since about 1966, have virtually unlimited depth capability and can handle payloads on the order of hundreds of kilograms. With manipulating arms they have been able to pick up small objects (rock and plant samples, lost tools and instruments) and have assisted in the recovery of large devices such as the nuclear weapon lost off Spain. They have also been used extensively for geologic research programs on the mid-ocean ridges in the North Atlantic and Eastern Pacific Oceans.

c. Deep Sea Drilling Ships

The vessel which has made the greatest impact on scientific observation of the subseafloor structure has been the Deep Sea Drilling Program's ship GLOMAR CHALLENGER[99]. This ship, which only began operations in 1968, is presently capable of drilling through the sediment and into hard basement rock in all depths, save the deep trenches. Standard oil exploration type drill pipe and bits are used. Penetration in hard basaltic and doleritic rock has been on the order of 500 m. Maximum sediment penetration has been appreciably greater (≈2 km). It is possible to install 11" diameter casing in holes up to 1 km deep. Manipulator ships such as the SEAPROBE can also penetrate several tens of meters into soft sediments by pumping water down the probe pipe. This "wash down" technique is also used by GLOMAR CHALLENGER to start its holes.

It should be noted that numerous oil exploration drilling ships built during the last 10 years have the capability of drilling very deep holes (≈6 km), large diameter holes (≈18" dia) in shallow waters (<600 m depth).

An important scientific result from the CHALLENGER drilling, which is relevant to borehole OBS deployment, is the observation that the geothermal gradients in the hard seafloor sediments and rocks may be comparable and perhaps lower than land surface gradients in some regions. This suggests that thermal convection of seawater in the borehole may be low enough to permit simple open hole seismometer installations. For example, in the small (≈4") diameter casing envisioned for future SRO-type borehole seismometer installations, the critical geothermal gradient necessary for convection to begin is estimated to be on the order of 10°C/km at 22°C[100,101]. Significantly, the gradient recently observed in a deep sea drilling borehole near the base of the sediment layer on the mid-Atlantic ridge (69-300 meters penetration interval) was on this order (13.6-20.4°C/km @ 8°C)[102]. Deep boreholes on cooler older crust at the ocean basin margins might be expected to show even smaller gradients, particularly within the high thermal conductivity basement rocks. In contrast land surface and near-seafloor sediment gradients are typically 35-80°C/km[98,103]. Also, deep seafloor boreholes are not subject to strong seasonal and diurnal effects due to solar heating variations and groundwater level changes. It appears therefore that, with the observed thermal gradient near the critical gradient, very little if any convection will occur in deep penetration seafloor boreholes. In any case, by sealing the seismometer at the bottom of the hole with high viscosity muds, convection effects can be sharply reduced.

2. Ocean Acoustic Communication

Routine data telemetry, vehicle navigation, and command and control functions are now carried out by most ocean research groups. Also, many marine geophysical exploration and oil service companies use these techniques. For example, it is now possible to track and, in some cases, control submersibles and tethered devices such as cameras, rock dredge and thermal probes to within a few meters at ranges up to 10 km using simple time-delay pulse systems[104]. In fact, phase measurement systems can provide a position fix precision of a few centimeters in the deep ocean[105].

Short range acoustic data telemetry, although used in some of the early OBSs, is routinely used for surface vessels to communicate with submarine vehicles and devices. Carrier frequencies on the order of 10 kHz are used to obtain maximum ranges of about 10-20 km with a 2 kHz bandwidth. Longer range acoustic telemetry is done in the 200-300 Hz band. CW systems operating in the SOFAR channel have achieved ranges in the order of 1000 km. For example, scientists at Woods Hole and the University of Rhode Island have now begun to routinely monitor neutrally buoyant, temperature and pressure sensing instruments floating in the NW Atlantic SOFAR channel using shore based hydrophones[106]. Similarly, fixed sonar sources and receivers are used to measure small acoustic fluctuations of the ocean's internal wave field over large distances[107]. The maximum useful bandwidth at these low carrier frequencies is thought to be only about 10 Hz. However, it is anticipated that at even lower carrier frequencies, say 50 Hz, ocean noise levels will be lower and a somewhat wider bandwidth and greater range may be attained[108].

In any event it should be pointed out that a 10 Hz bandwidth is probably more than adequate for a quasi-realtime seismic data communication with a single seafloor station. This is because observed micro-earthquake activity even in such tectonically active areas as the Japan Trench and the Mid-Atlantic Ridge is only on the order of 100 events per day. Since maximum event durations are usually less than 1 minute, this means that by using automatic event detection techniques and a buffered digital data storage system, simple time expansion of the event wavetrains could easily provide adequate bandwidth. For example, a time expansion factor of 5 would give a bandwidth of 50 Hz and require an average data transmission delay of only 5 minutes. Transmission of three-component data would involve a 15 minute delay.

3. Satellite Telemetry and Navigation

Although the use of satellites for telecommunication of data between land sites has been commonplace for many years, only recently has it become available to marine scientists. It is now possible to use the U.S. Navy's stationary orbit SEASAT system to transmit data from ships and moored surface buoys in the Atlantic, Indian, and Pacific oceans to U.S. land stations. This system would be more than adequate for a real-time OBS data monitoring link. Ocean bottom units could telemeter data, either acoustically or via cable, to a satellite-linked surface buoy. One buoy could probably collect acoustic data from an array of OBSs up to 40 km in diameter without using cables at all. In fact, if the acoustic link were to use the SOFAR channel, even larger arrays could be installed. However, in this latter case, short cables would be necessary to connect each OBS to an overhead sonar transmitter moored at the channel axis depth.

It should also be noted that satellites now provide accurate positioning information virtually anywhere on the world's oceans. Routine position fixing of ±200 meters is now available to most Navy, ocean research, and large commercial ships. This capability means that it is possible to re-visit sites where previous measurements and deployments were made. thus, by attaching acoustic transponder beacons to an ocean bottom device, a surface ship or submersible can simply "home in" on the instrument for its recovery. The risk of losing expensive seafloor devices has been drastically reduced. This technique, which is now routinely used aboard ocean research and oil exploration ships has only become available since 1968.

4. Deep Ocean Moorings

The durability of both surface and sub-surface moorings has markedly improved during the 1970's. This is a result of extensive design analyses and field testing undertaken during the Mid-Ocean Dynamics Experiments (MODE) and the Global Atmospheric Research Program (GARP) sponsored by ONR and NSF[109]. For those studies, large sub-surface arrays of current meters and temperature sensors were moored in the deep ocean along with surface buoys for air-sea interaction observations. Many of the moorings were deployed for as long as 6 months, some much longer. The work clearly showed that it is not unreasonable to consider long term deployment in deep water (>[illegible]000 m) for periods on the order of a year. In fact, the National Oceanic and Atmosphere Administration (NOAA) is currently operating several long term deep water surface moorings for weather forecasting purposes which telemeter their observations to satellites. Ultimately it may be possible to have such moorings replace all the remaining deep ocean weather ships operated by the Coast Guard.

5. Deep Ocean Power Sources

The rapid expansion of ocean science and space instrumentation in the late 1960's has required the development of large, long term remote power sources. Various types of chemical cells (lithium, cadmium) are now available which can continuously produce several tens of watts over a 3-6 month period. These are usually more than adequate for most research applications. For long term high power requirements such as in satellites and some sonar systems, nuclear fuel cells have also been developed. These units can provide hundreds of kilowatts for many years.

Nuclear power units are particularly attractive for OBS regional research installations as compared to land stations. It may be that a host nation would not allow land stations to be nuclear powered. Thus, these stations would be dependent on local power or batteries. A nuclear powered OBS system would be completely secure from power interruptions. OBS seismic stations are an obvious application of available nuclear power technology.

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An analysis of current ocean bottom seismometer technology has revealed that conventional, free-fall devices which simple rest on the surficial seafloor sediments could provide portable stations with short period performance only equivalent to the higher noise land stations located on islands. However, by emplacing borehole-type seismometers beneath the surficial seafloor sediments, the broadband performance of ocean bottom stations could prove superior to the best land stations. In fact, by combining "state of the art" broadband digital seismometers with modern deep sea drilling and ocean acoustic or satellite telemetry methods, permanent subseafloor stations with essentially real-time communication are entirely feasible. A plan for preliminary seismic research is suggested.

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